Modeling of Two-dimensional Five-harness Woven SiC/SiC Ceramic Matrix Composites

Subodh K. Mital
The University of Toledo
Toledo, Ohio, U.S.A.

Kuang C. Liu
Arizona State University
Tempe, Arizona, U.S.A.

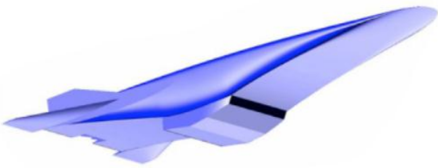
Brett A. Bednarcyk and Steven M. Arnold
NASA Glenn Research Center
Cleveland, Ohio, U.S.A.

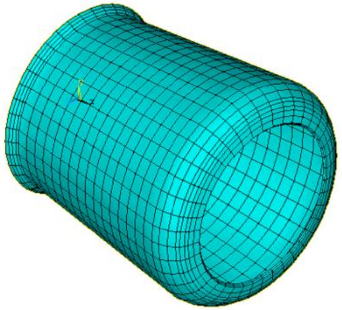
Outline

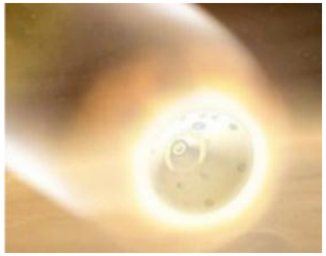
- Introduction/Background
- Analysis Methods
- Elastic Results
  - Homogenized Composite Properties
  - Local Stress Fields
- Creep Modeling
- Multi-Scale Generalized Method of Cells (MSGMC)
  - Impact of material and architectural parameters on composite properties
- Conclusions

Ceramic Matrix Composites (CMCs) are Advantageous for High-Temperature Applications

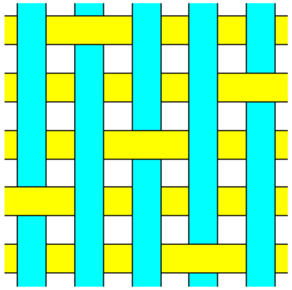
- Typical higher operating temperature limits as compared to advanced metals
- Lightweight, tailorable properties
- Potential candidate materials in many aerospace structural applications





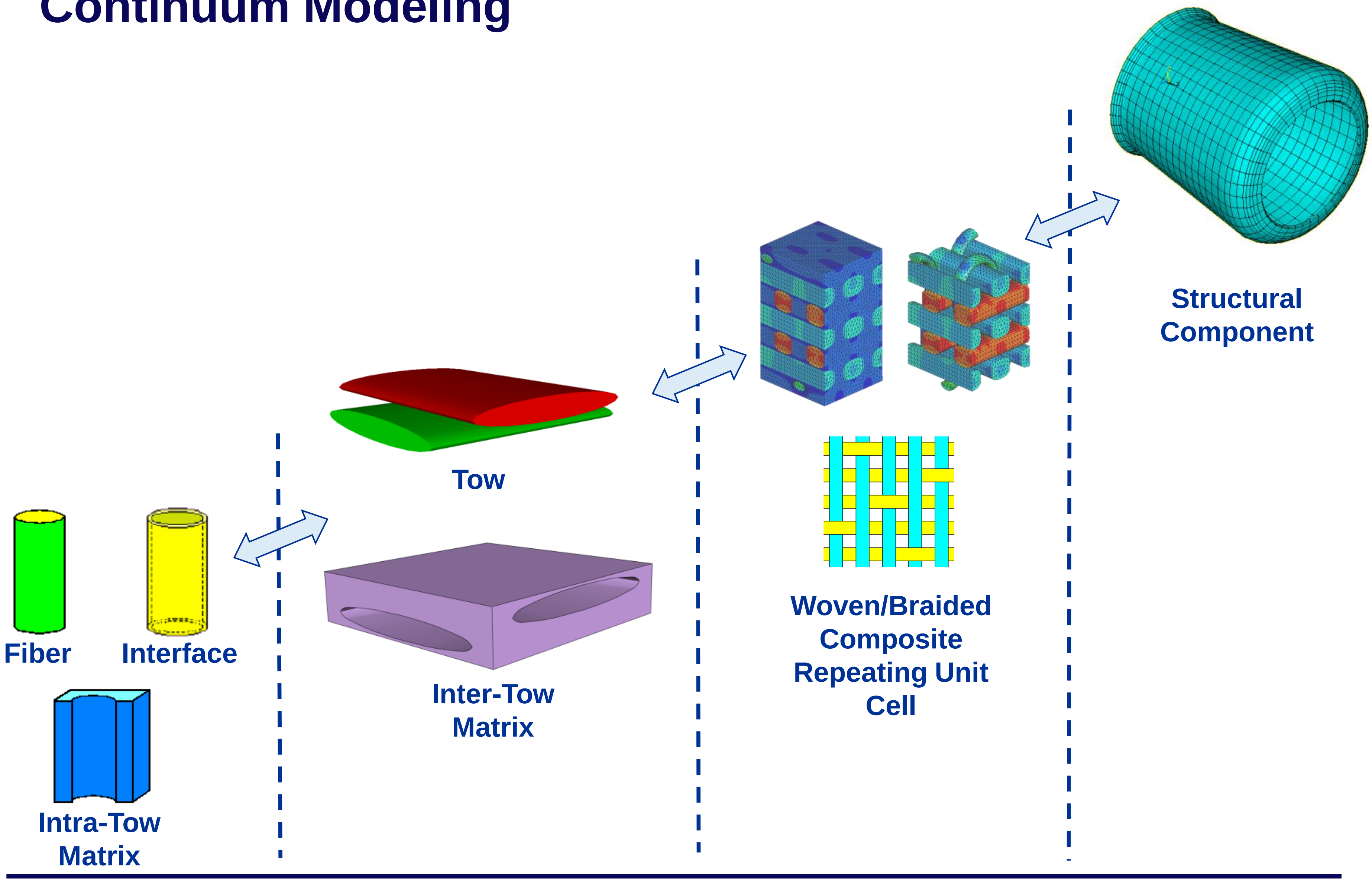


Objective of Present Work: Examine and Assess Approaches for Modeling Woven CMCs

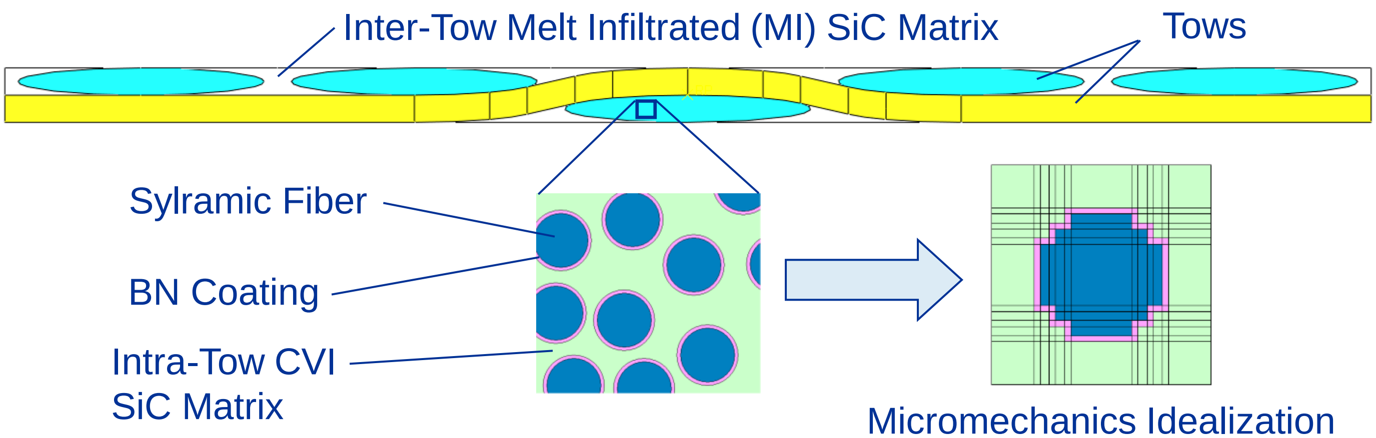


- Material description –
  - Fiber is woven in a fabric preform of desired architecture such as plain weave, five-harness satin weave
  - Woven fabric is stacked in multiple layers
  - An interfacial coating is deposited on all fiber surfaces usually by a chemical vapor infiltration (CVI) process
  - The preform is then infiltrated by a silicon carbide matrix using the CVI process
  - The remaining porosity is filled either continuing to deposit the SiC matrix uisng the CVI process or in some cases using a slurry-cast melt-infiltration (MI) process.

Multiple Scales in Woven/Braided Composite Continuum Modeling



Given Constituent Properties, Determine Effective Tow Properties



Note: Porosity accounted for in SiC matrix properties

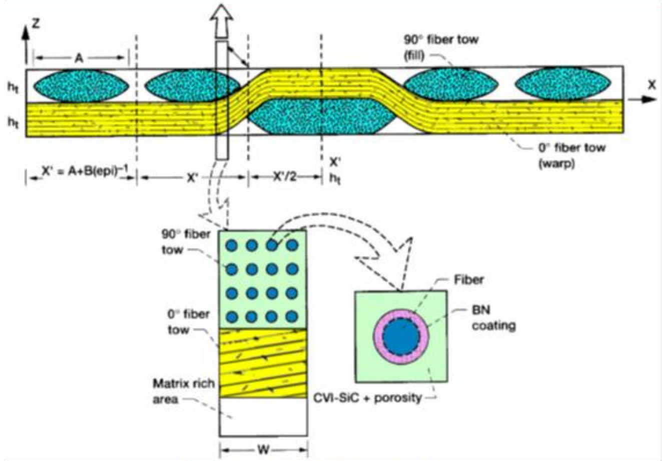
Fully Dense $E_{SiC} \approx 420$ GPa

Correlated Constituent Properties*	iBN Sylramic Fiber		CVI-BN Coating		Intra-Tow CVI-SiC		Inter-Tow MI-SiC	
	21 ºC	1204 ºC	21 ºC	1204 ºC	21 ºC	1204 ºC	21 ºC	1204 ºC
Modulus (GPa)	380	365	21	14	380	358	310	276
Poisson's ratio	0.17	0.17	0.22	0.22	0.17	0.17	0.17	0.17
CTE (10^{-6}/ ºC)	4.6	8.0	5.2	10	4.6	9	4.7	9
Th. Cond. (W/mK)	43	21	3.1	1	70	33	68	25

*Ref: Murthy, P.L.N., Mital, S.K., and DiCarlo, J.A., NASA /TM-1999-209173 + in-house GRC properties

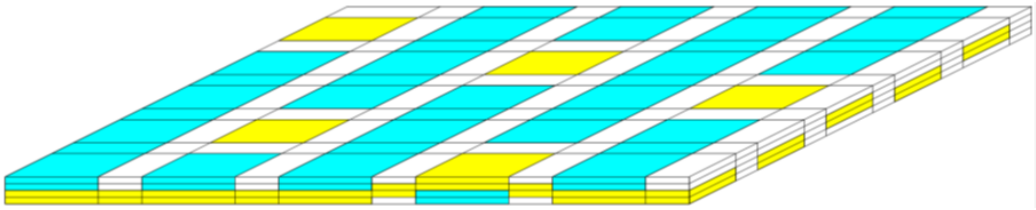
Analysis Methods Vary Based on Capabilities, Fidelity, and Computational Expense

- Micromechanics Based (Analytical) Methods –
  - Laminate Approximation
  - W-CEMCAN - Generalized Method of Cells (GMC)



W-CEMCAN

*Ref: Mital, S.K., Murthy, P.L.N., and Chamis, C.C., NASA/TM-1996-107165.



Generalized Method of Cells

1-Step and 2-Step Methods

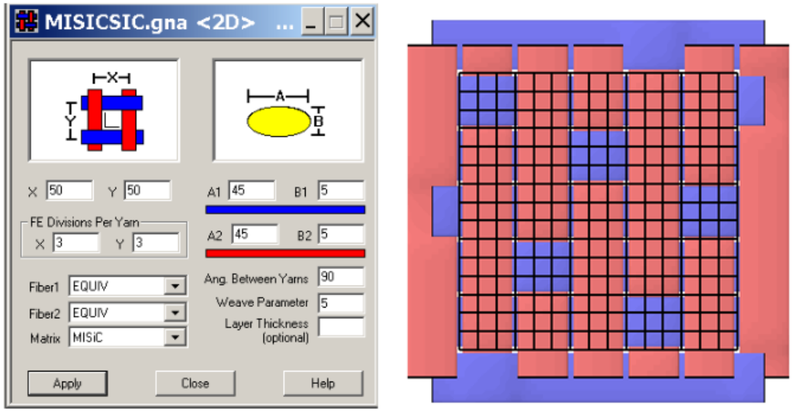
Ref: Aboudi, J., Mech. Adv. Materl. Struct. 11, 329–366, 2004.

- **Also have High Fidelity Generalized Method of Cells (HFGMC)**
- **Accounts for tow directionality**
- **Elliptical tow shape**
- **Account for tow undulation**

Analysis Methods Vary Based on Capabilities, Fidelity, and Computational Expense

- Hybrid Methods –

- User friendly
- Models many types of 2-D and 3-D architectures

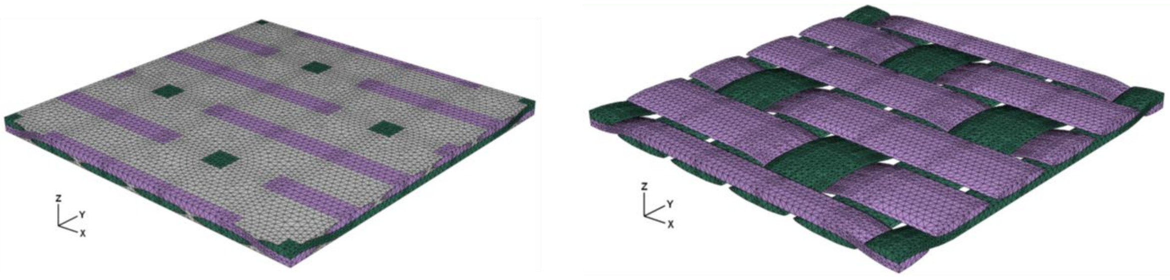


pcGINA

Ref: Gowayed, Y.A, Ph.D. Thesis, N.C. State University, 1992.

- Numerical Methods (2-D and 3-D Finite Element Analyses)-

- Accurate
- Inefficient and expensive

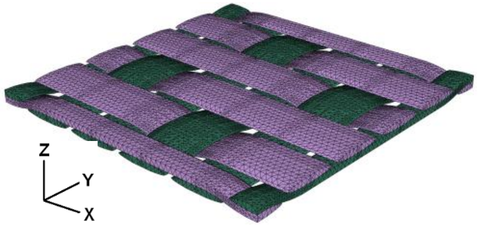


3D Finite Element Analysis (Abaqus)

Elastic Properties at Room Temperature

	Multiscale Lam. Theory		W-CEMCAN	GMC-3D		HFGMC		pcGINA	FEA		Avg. Exp.
	Rect. Tow	Cross Tow		1-step	2-step	2-D	3-D		2-D	3-D	
E_x (GPa)	254	253	266	233	252	253	247	248	253.7	**251.9**	**252**
E_y (GPa)	254	253	266	233	252	234	247	248	233.6	**251.9**	**252**
E_z (GPa)	183	180	178	183	183	163	183	174	163.3	**180.2**	**~82**
ν_{xy}	0.130	0.129	0.12	0.125	0.127	0.126	0.121	0.12	0.139	**0.129**	**0.13**
G_{xy} (GPa)	77.6	76.4	78	70.7	74.5	67.6	71.4	102	72.6	**76.5**	–
κ_x (W/m-k)	TBD	TBD	42	37.4	41.3	TBD	TBD	42	TBD	TBD	50
κ_z (W/m-k)	TBD	TBD	30	30.3	30.3	TBD	TBD	32	TBD	TBD	25
CTE_x (10^{-6}/^oC)	TBD	TBD	4.63	4.64	4.66	TBD	TBD	4.2	TBD	TBD	2.7
Ex. Time (s)	**0.015**	**0.015**	**<1**	**0.08**	**–**	**0.22**	**2.9**	**~4**	**60***	**2640***	**–**

*For 4 Load Cases



Elastic properties within ~7%

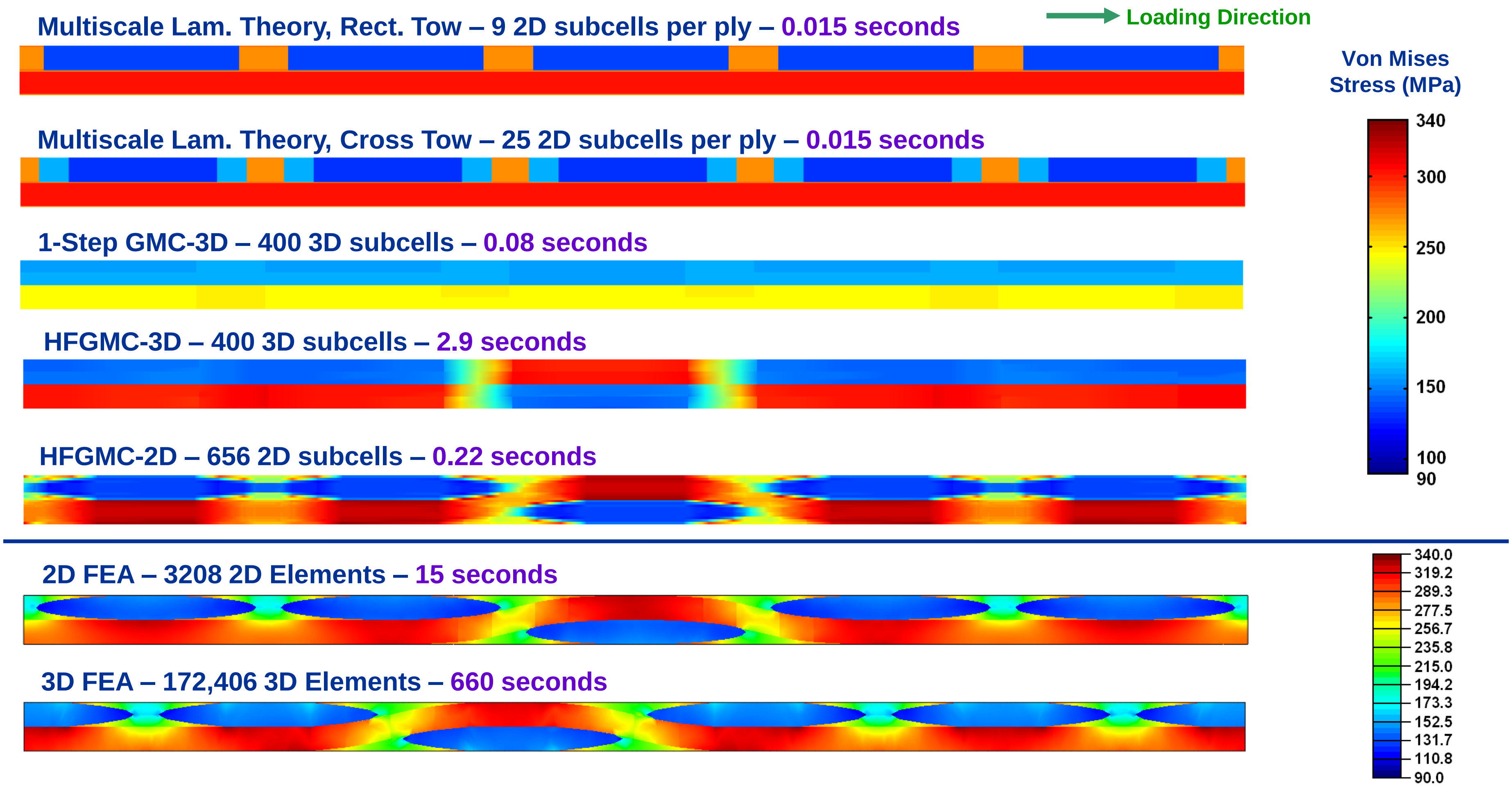
Constituent properties known no better

Experimental repeatability no better

Note: Execution times based on Intel dual core X7900 @ 2.8 GHz, 4 GB RAM

Efficient Methods Still Give Reasonably Accurate Approximations of Local Stress Fields

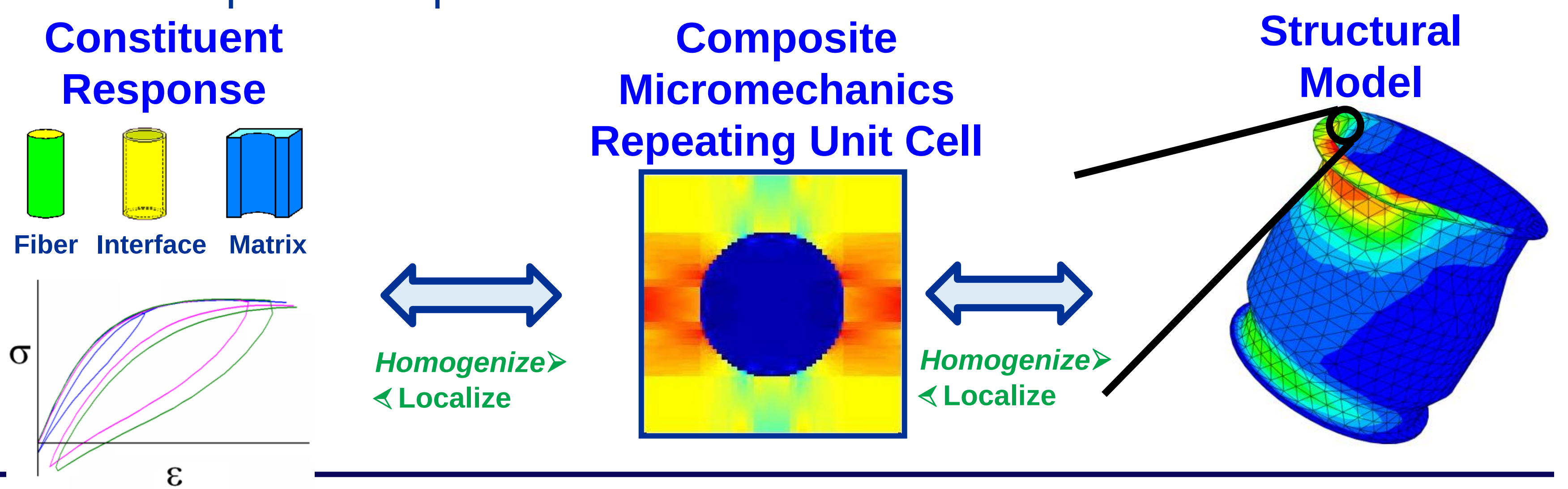
- Von Mises stress fields predicted by models
  - 1204 ºC, applied in-plane strain of 0.1%



ImMAC Software Suite

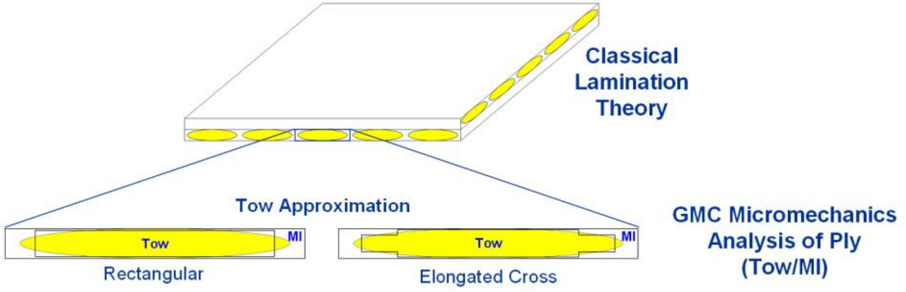
Integrated multiscale Micromechanics Analysis Code

- Consists of MAC/GMC (stand-alone), FEAMAC(implemented within ABAQUS) and HyperMAC (implemented within HyperSizer) software codes.
- ImMAC is software released by NASA GRC/RXL for ***multiscale analysis of composite structures***
- It links the behavior of a structure to the behavior of the composite constituent materials
- The key link between the scales is micromechanics, which provides the composite response based on the constituent behavior

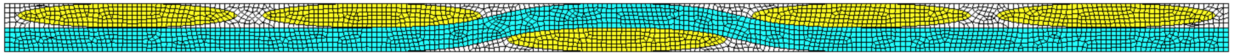


Creep Modeling

- **Multiscale Lamination Theory**
  - Rectangular tow
  - Cross-shaped tow



- **2D FEA**

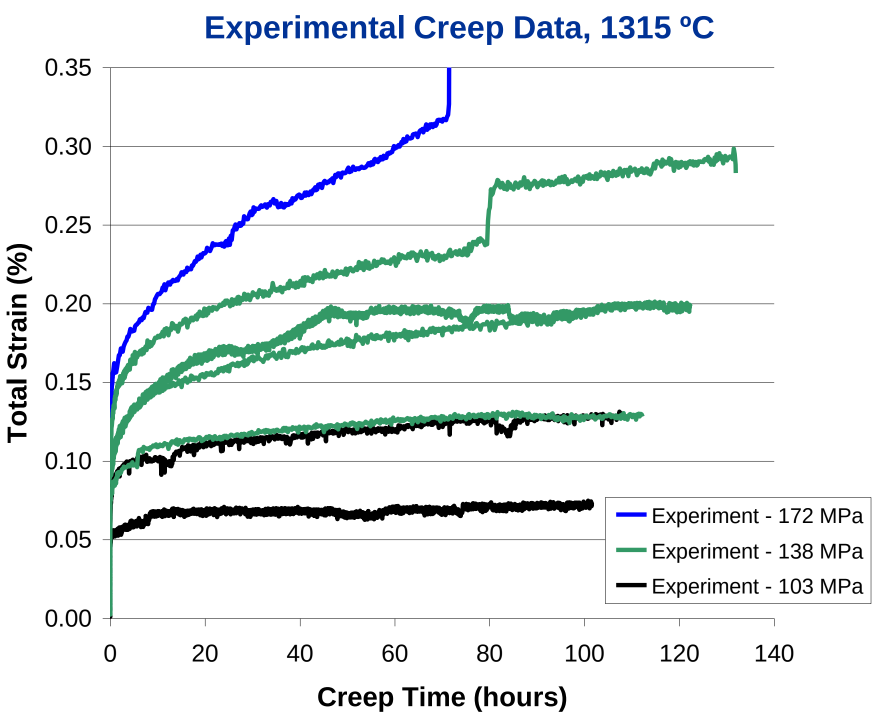


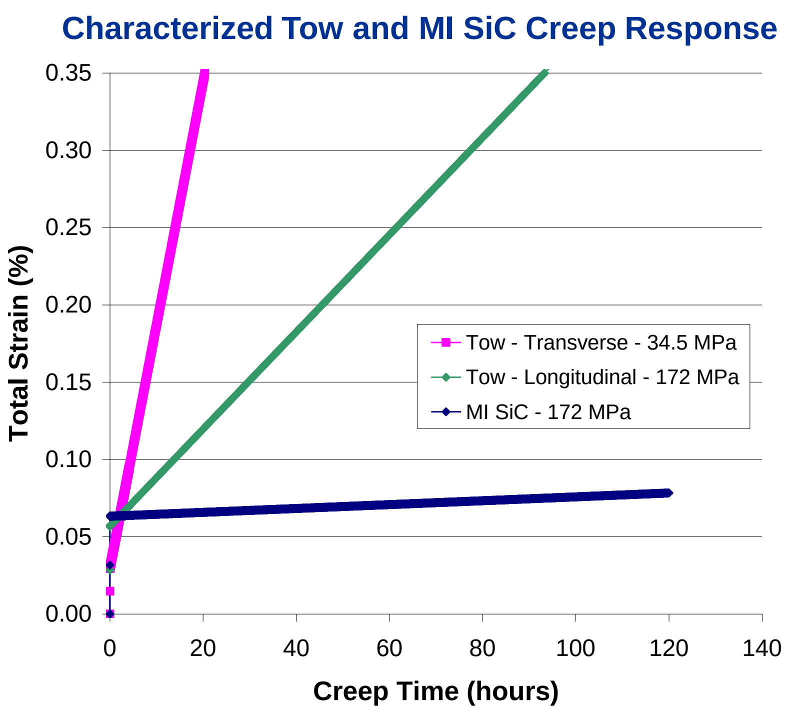
- Transversely isotropic power law creep model used to model creep of tows
- Five material parameters for transversely isotropic tows and three parameters for isotropic matrix
- These parameters must be backed out from available measured composite creep curves

Creep Parameters of Tows and Matrix Not Known

Efficiency is Critical when Backing Out Nonlinear Model Parameters

- Typical to run hundreds of cases to determine parameters
  - Used efficient Multiscale Lam. Theory approach to obtain parameters
- Utilized creep test results at 1315 ºC
- Isotropic MI SiC: κ_T = 55 MPa, $\mu = 3.7\times10^{10}$ MPa·s, n = 1, η = 1, ω = 1
- Trans. Iso. Tow: κ_T = 6.9 MPa, $\mu = 6.9\times10^{10}$ MPa·s, n = 3.5, η = 5, ω = 5

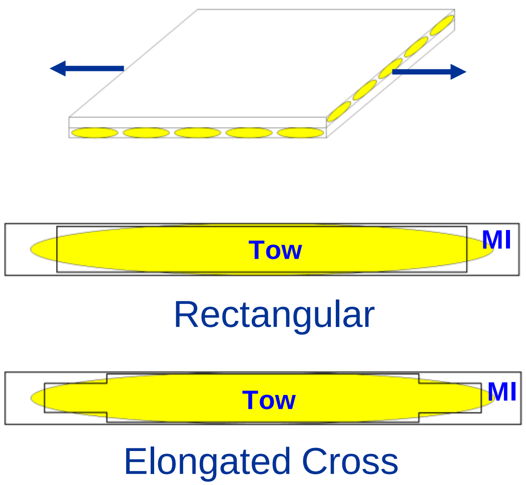


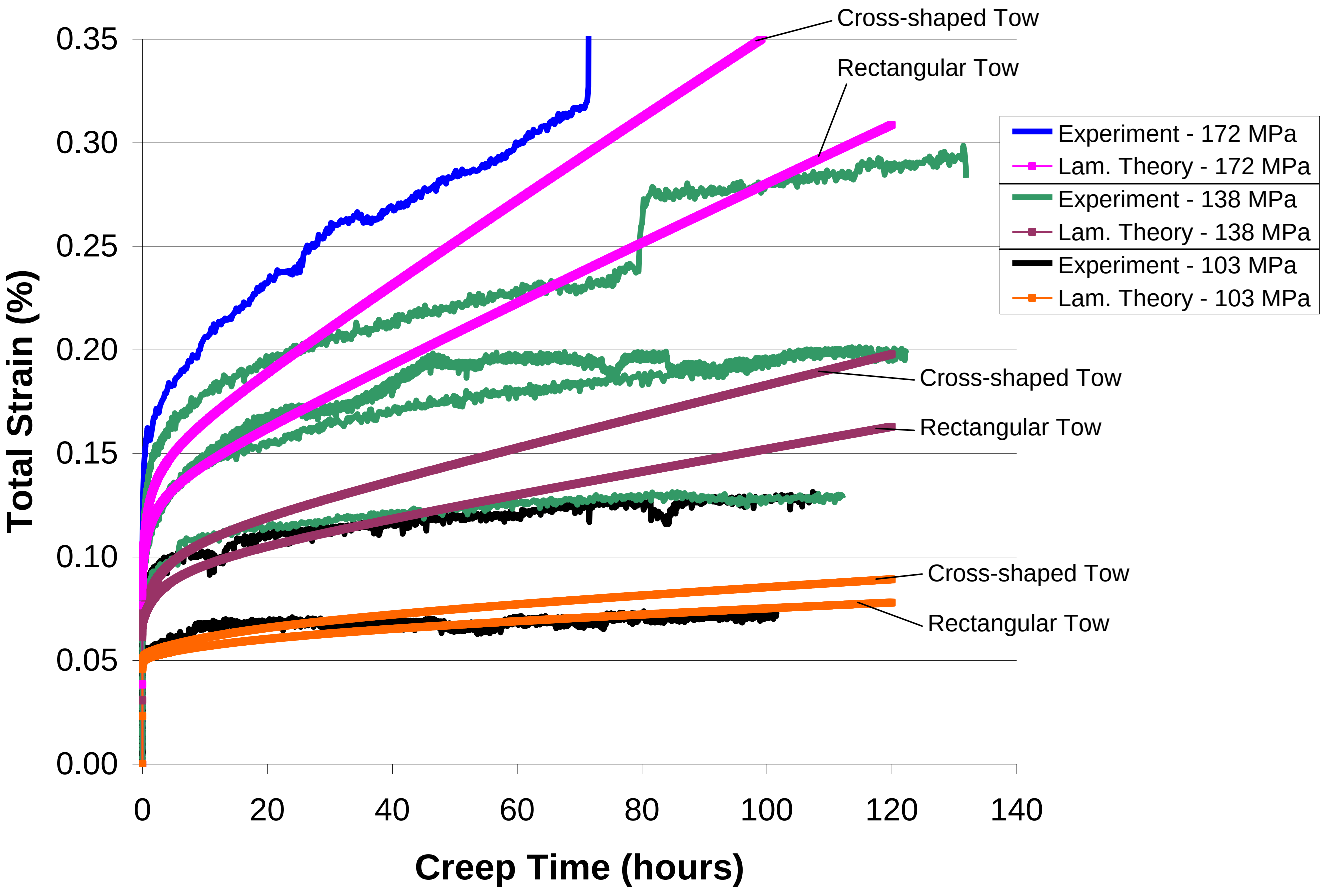


Multiscale Lam. Theory Captures Primary and Secondary Creep, Even Though Constituents have Only Secondary

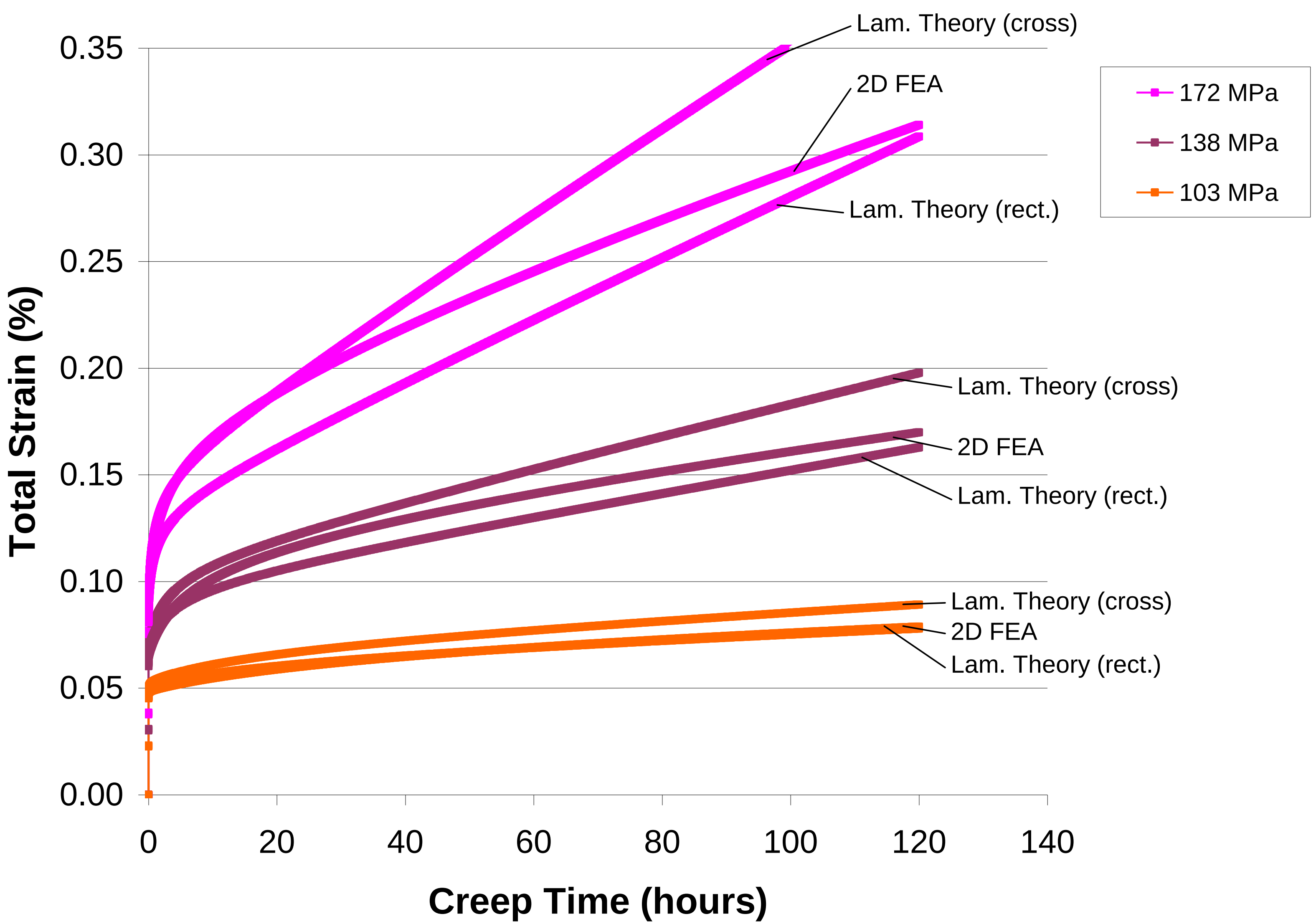
- Stress redistribution from relaxation drives apparent primary creep
- Effect of tow shape representation much more pronounced
  - Recall E affected only by ~0.5 %

- 2340 time increments
- Execution times:
  - 0.6 seconds
  - 1.0 seconds

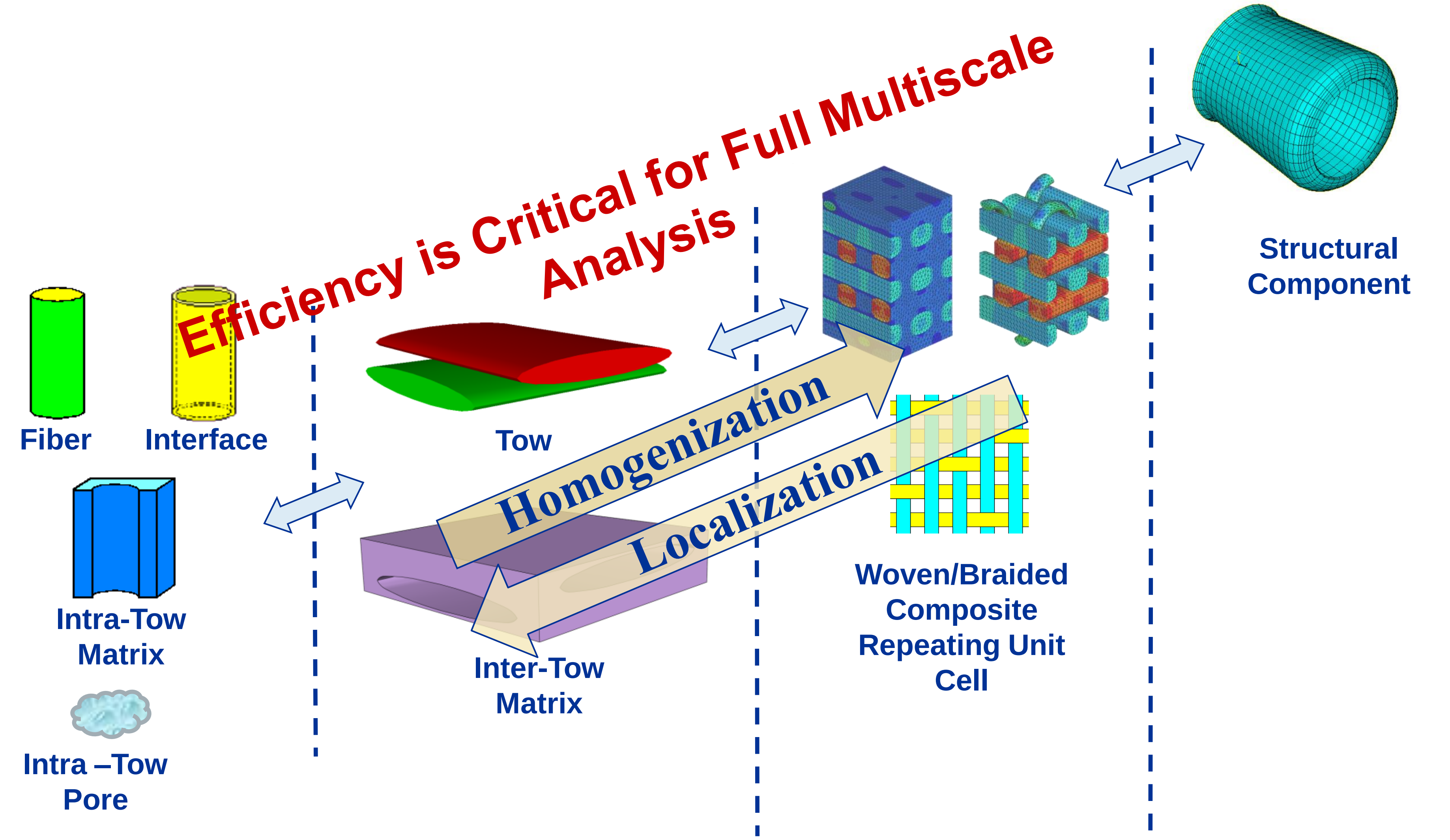




Methods Give Similar Macroscopic Creep Predictions

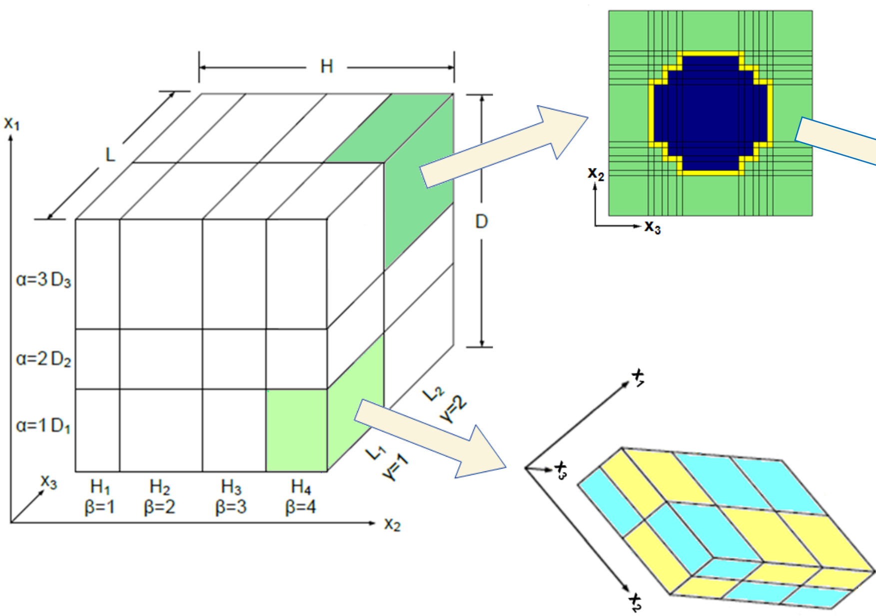


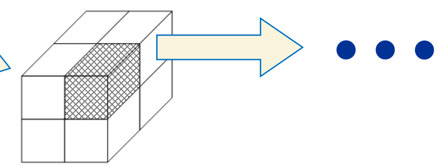
Multiscale Generalized Method of Cells (MSGMC) For Concurrent Analysis of Woven/Braided Composites



Multiscale Generalized Method of Cells(MSGMC) Overview

- Newly developed recursive GMC methodology
  - Each length scale in each subcell can call a separate GMC analysis
- Works for any arbitrary multiphase material
  - Elastic / Inelastic / Damage

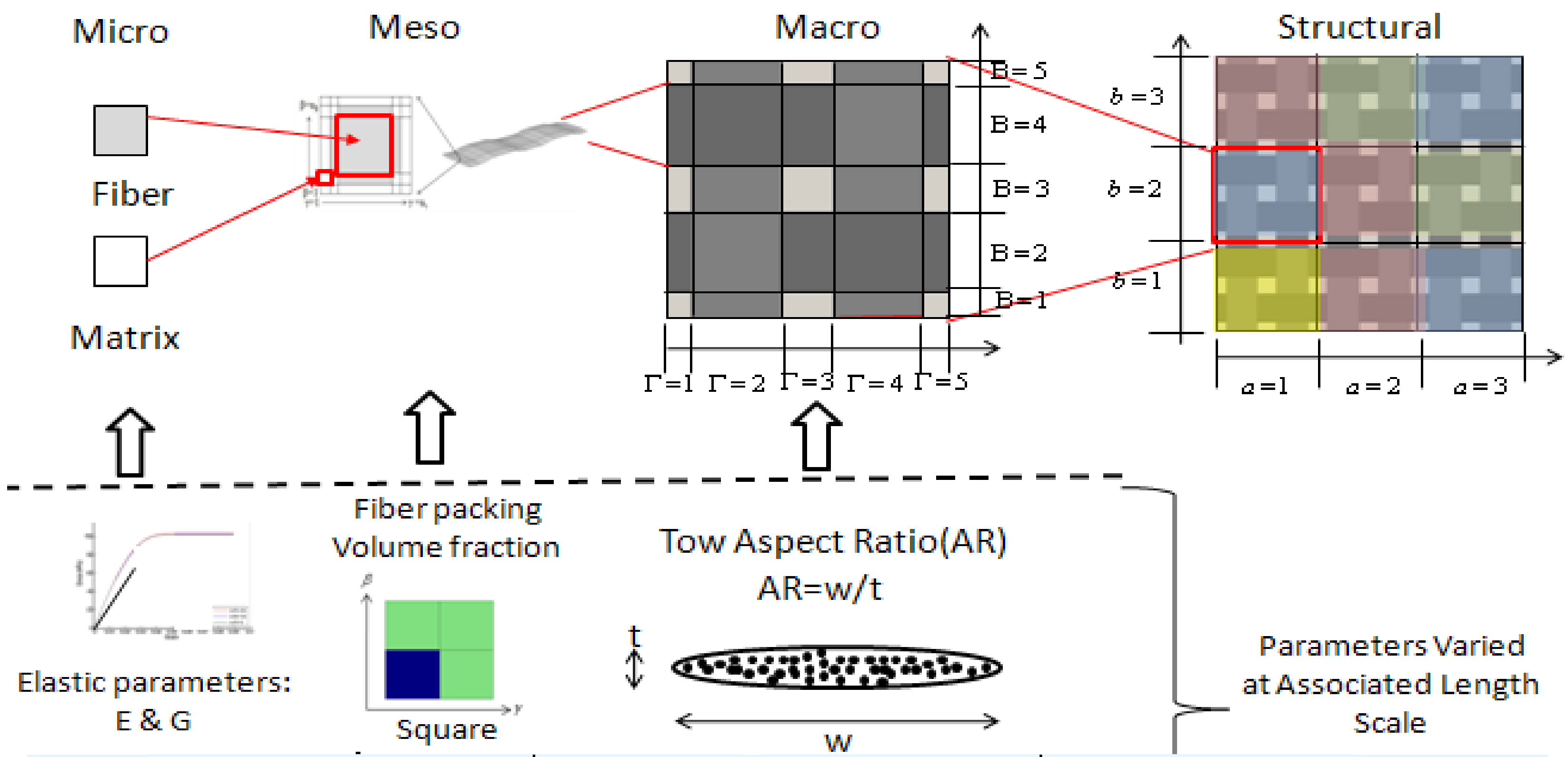




Multiscale analysis can determine local stresses at different length scales

$$\sigma^{\{\alpha\beta\gamma\}\{\beta g\}} = C^{\{\alpha\beta\gamma\}\{\beta g\}} A^{\{\alpha\beta\gamma\}\{\beta g\}} A_{tt}^{\{\alpha\beta\gamma\}} A_{ip}^{\{\beta\gamma\}} \Delta\varepsilon$$

Study Effects Of Micro, Meso, And Macro Parameters on Macroscale Response



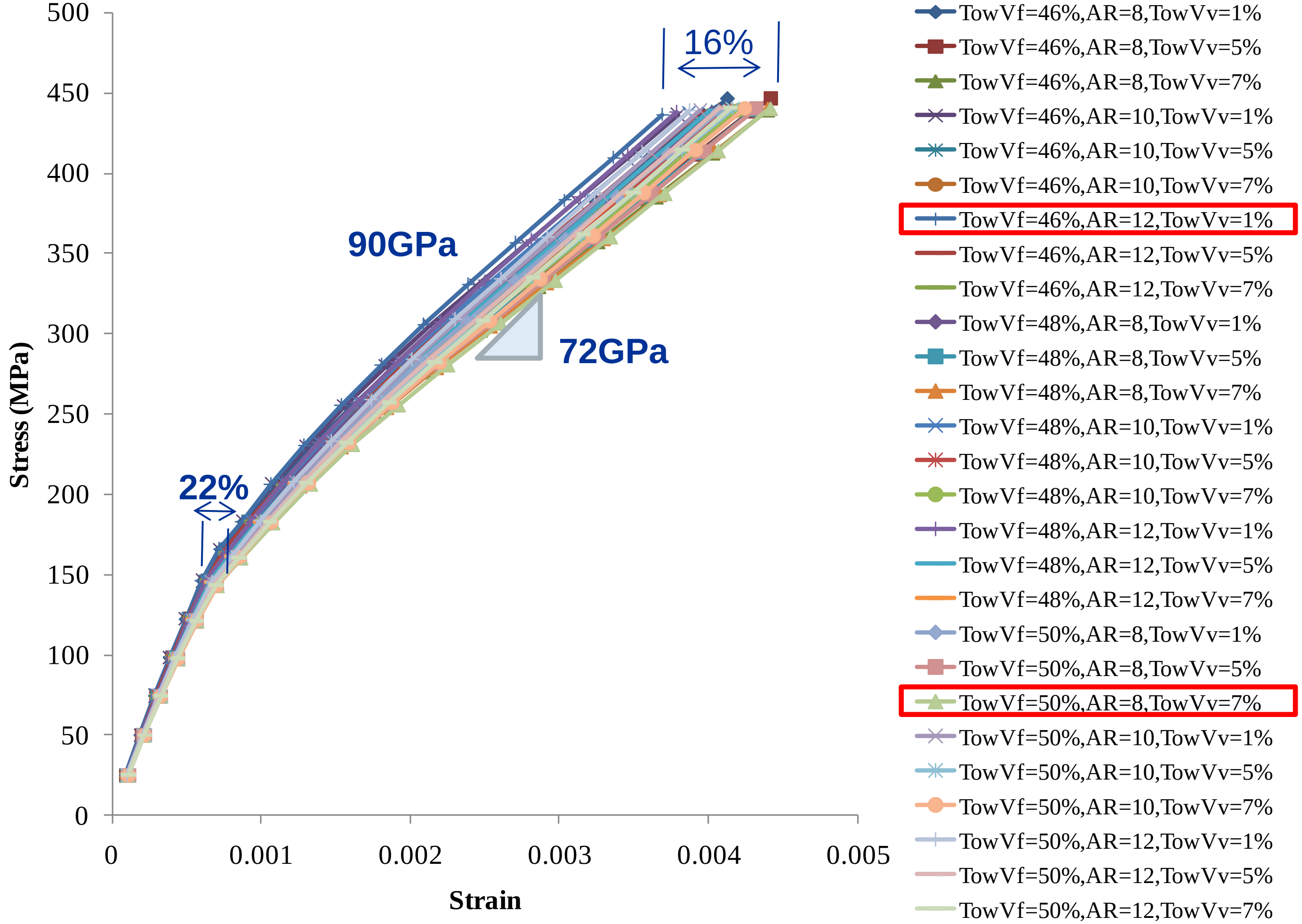
Architectural Parameter	Relevant Length Scale	Values
Tow Fiber Volume Fraction	Meso	0.46,0.48,0.50
Tow Void Volume Fraction	Meso	0.01,0.05,0.07
Tow Aspect Ratio	Macro	8,10,12

Range Of Macro Response Curves Given the 27 Variations In Architectural Parameters

Utilized Localized Void Model

Architectural Variations clearly contribute to variation in measured material response.

- **Initial Modulus ≈ 24%**
- **UTS ≈ 2%**
- **1st matrix cracking ≈ 16%**
- **Post matrix cracking Modulus ≈ 24%**
- **ε_f impacted ≈ 16%**



Conclusions

- **Elastic Response –**
  - **Various methods for modeling 5 harness satin weave SiC/SiC composite were examined.**
  - **Methods generally fall in three categories: analytical, hybrid and numerical.**
  - **All methods do reasonably good job of predicting elastic properties as well as elastic stress fields.**
  - **Computational efficiency is the discriminator as analytical methods are orders of magnitude more efficient than fully numerical methods. It is important for multiscale analysis.**

- **Creep Behavior –**
  - **Two methods (multiscale laminate analyses and 2-D FEA) were examined for modeling creep behavior.**
  - **Efficient methods are needed for backing out creep model parameters.**
  - **Creep/relaxation process among long. tows, trans. tows, and matrix is complex and drives the response.**
  - **Both methods agree reasonably well with experimental data.**

Conclusions (contd.)

- **Multiscale Analysis of Woven Composites -**
  - **Demonstrated that a synergistic analysis using the multiscale generalized method of cells (MSGMC) can accurately represent woven CMC tensile behavior (loading/unloading).**
  - **Failure mechanisms are captured via local continuum damage model.**
  - **Variations in Weave Parameters (micro, meso, and macro) appear to contribute to variation in measured material macrolevel response.**